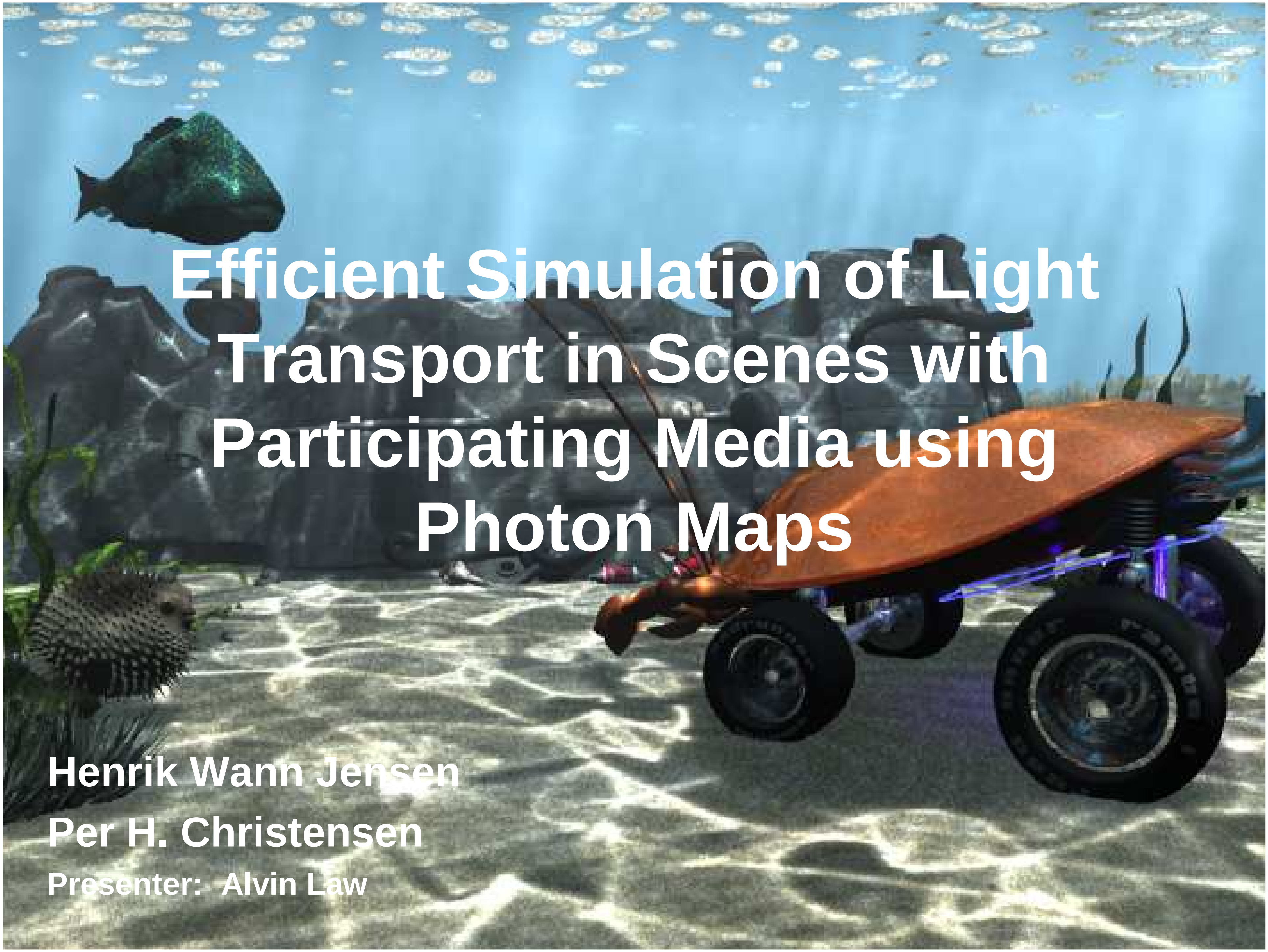


Efficient Simulation of Light Transport in Scenes with Participating Media using Photon Maps

Henrik Wann Jensen

Per H. Christensen

Presenter: Alvin Law

Photon Mapping for Surfaces

- Two pass algorithm
  - Pass 1: trace photons to make maps
  - Pass 2: render image using photon maps
- Separate maps for different uses
  - Global photon map records $L(S|D)^+D$ paths
  - Caustics photon map records LS^+D paths
- Maps are balanced kd-trees for efficient storage and lookup

Pass 1: Creating the Photon Maps

- Emit photons from light sources (this can be importance sampled)
- Trace photon (much like a ray) through scene, bouncing off surfaces
  - Photon not recorded on first bounce (do not double count direct illumination)
  - Photon energy modulated by each surface
- Photon paths terminated via russian roulette

Photons

- Small packet of energy
- Records information from tracing
  - Photon position
  - Splitting plane
  - Incoming direction
  - Power

Pass 2: Rendering

- Direct illumination done as usual
- Indirect illumination estimated with global photon map
  - Indirect ray intersects surface at point p
  - Gather N nearest photons on surface

$$L_r(x, \vec{\omega}) \approx \sum_{p=1}^{n} f_r(x, \vec{\omega}_p', \vec{\omega}) \frac{\Delta \Phi_p(x, \vec{\omega}_p')}{\pi r^2}$$

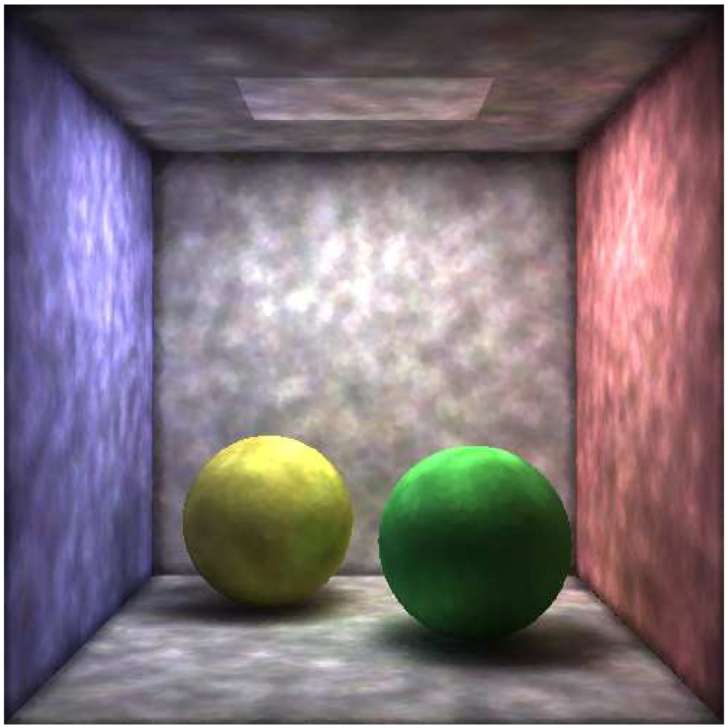
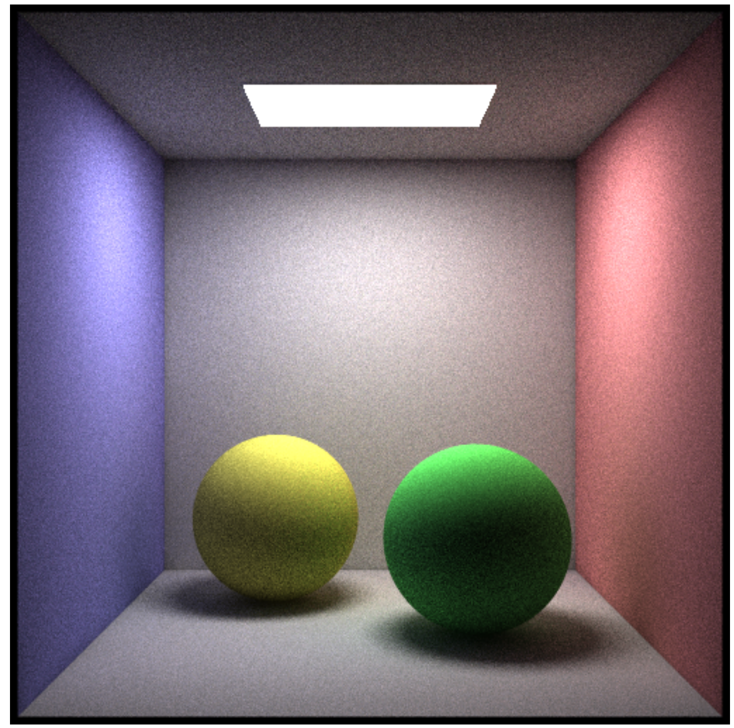
- Caustics rendered with caustics photon map

Pass 2: Rendering

- Total equation
  - Direct illumination
  - Specular reflections
  - Caustics
  - Indirect illumination

$$
\begin{aligned}
L_r &= \int_\Omega f_r L_{i,l} \cos\theta_i \, d\omega_i + \\
& \int_\Omega f_{r,s} (L_{i,c} + L_{i,d}) \cos\theta_i \, d\omega_i + \\
& \int_\Omega f_{r,d} L_{i,c} \cos\theta_i \, d\omega_i + \\
& \int_\Omega f_{r,d} L_{i,d} \cos\theta_i \, d\omega_i
\end{aligned}
$$

CS665 Photon Mapper

Rendered on Pentium IV 3.0 GHz in 444 seconds (7.4 minutes) using 25 samples per pixel with 171,880 photons. Created by Alex Liberman and Alvin Law. Left – map visualization. Right – final image.

Jensen's Tasty Cognac

Rendered on a P-90 in 4 hours using 64 samples per pixel with approximately 200,000 photons. Mmmm… cognac…

Photon Mapping and Participating Media

- Third volume photon map to store photons interacting with participating media
  - Store photons explicitly within the volume
  - Can be done without altering underlying algorithms
- Advantages
  - Photons can be concentrated to represent intense illumination
  - Participating media does not have to be discretized
  - Anisotropic scattering can be handled with incoming direction of photon
  - Faster than standard Monte Carlo techniques

Volume Photon Map

- Used to estimate indirect illumination of participating media
- Only store photons interacting with participating media (scattered or absorbed) not coming directly from light source
- Russian roulette used for termination
  - Decide whether photon is scattered or absorbed
    - Probability of scattering: scattering albedo $\sigma(x)/\kappa(x)$
    - New direction of scattered photon chosen based on phase function at x

Estimating radiance

Relationship between scattered flux and radiance L in participating medium:

$$L(x,\vec{\omega}) = \frac{d^2\Phi(x,\vec{\omega})}{\sigma(x)\,d\omega\,dV}$$

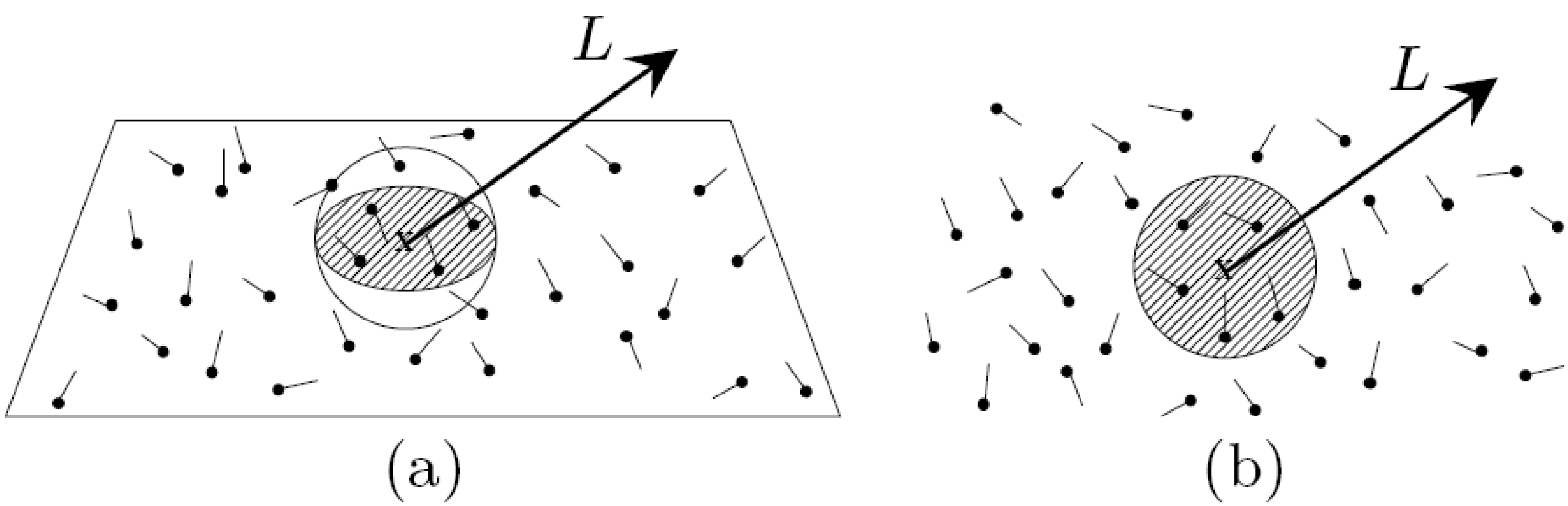
Solving for radiance:

$$\begin{aligned}
L_i(x,\vec{\omega}) &= \int_\Omega f(x,\vec{\omega}',\vec{\omega})\,L(x,\vec{\omega}')\,d\omega' \\
&= \int_\Omega f(x,\vec{\omega}',\vec{\omega})\,\frac{d^2\Phi(x,\vec{\omega}')}{\sigma(x)\,d\omega'\,dV}\,d\omega' \\
&= \frac{1}{\sigma(x)}\int_\Omega f(x,\vec{\omega}',\vec{\omega})\,\frac{d^2\Phi(x,\vec{\omega}')}{dV} \\
&\approx \frac{1}{\sigma(x)}\sum_{p=1}^{n} f(x,\vec{\omega}'_p,\vec{\omega})\,\frac{\Delta\Phi_p(x,\vec{\omega}'_p)}{\frac{4}{3}\pi r^3}
\end{aligned}$$

Nearest Photon Gathering

(a) surface gathering: over area

(b) volume gathering: over volume



Calculating In-scattered Radiance

Indirect contribution:

$$L_{i,i}(x,\vec{\omega}) \approx \frac{1}{\sigma(x)} \sum_{p=1}^{n} f(x,\vec{\omega}'_p,\vec{\omega}) \frac{\Delta\Phi_{p,i}(x,\vec{\omega}'_p)}{\frac{4}{3}\pi r^3}$$

Final formula:

$$L_i(x,\vec{\omega}) = L_{i,d}(x,\vec{\omega}) + \frac{\sigma(x)}{\kappa(x)} L_{i,i}(x,\vec{\omega})$$

Rendering

- Surfaces rendered with caustics and global photon maps as before
- Rays traveling through participating media computed with adaptive ray marching algorithm

$$
\begin{aligned}
L(x_k, \vec{\omega}) &= \alpha(x_k)\, L_e(x_k, \vec{\omega})\, \Delta x_k \\
&+ \sigma(x_k)\, L_i(x_k, \vec{\omega})\, \Delta x_k \\
&+ e^{-\kappa(x_k)\, \Delta x_k}\, L(x_{k-1}, \vec{\omega})
\end{aligned}
$$

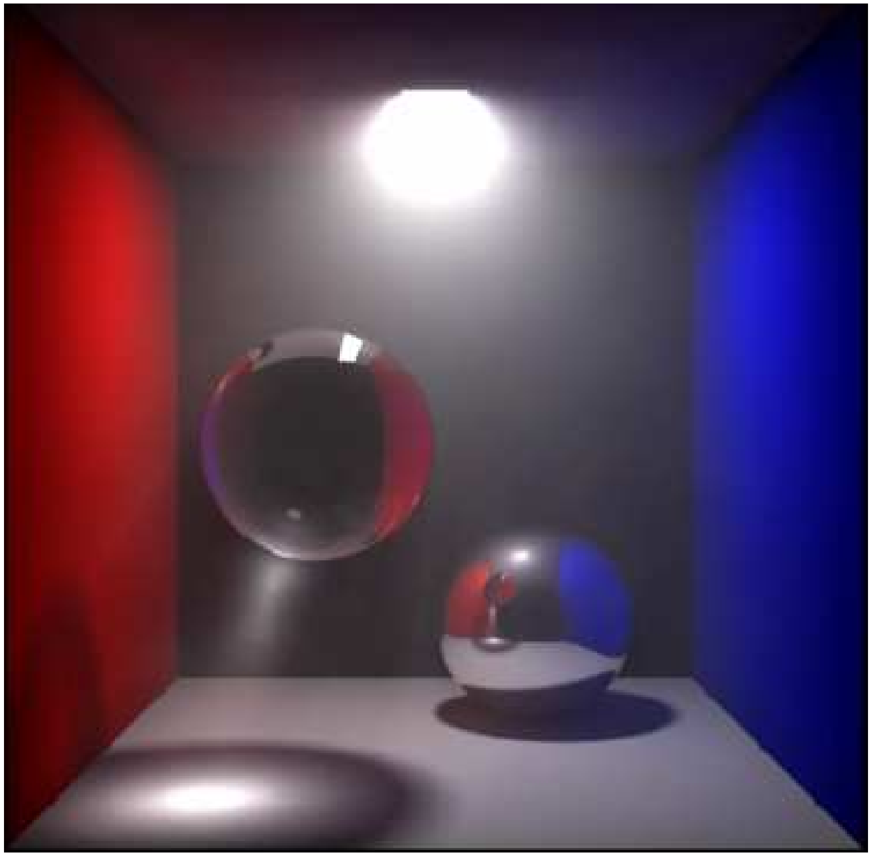
Results

- Photon mapping for participating media works well
- Maps are decoupled from geometry – allows for easy scaling to complex scenes
- Radiance estimate works surprisingly well with only 50-100 photons per estimate
- Issue – gathering near edge of medium
  - Sphere extends outside medium, resulting in estimated density of photons being too low
  - False photons might be included in the estimate
  - Can be avoided by looking at incoming direction of photons
- Blurring artifact of photon gathering

Images From the Paper

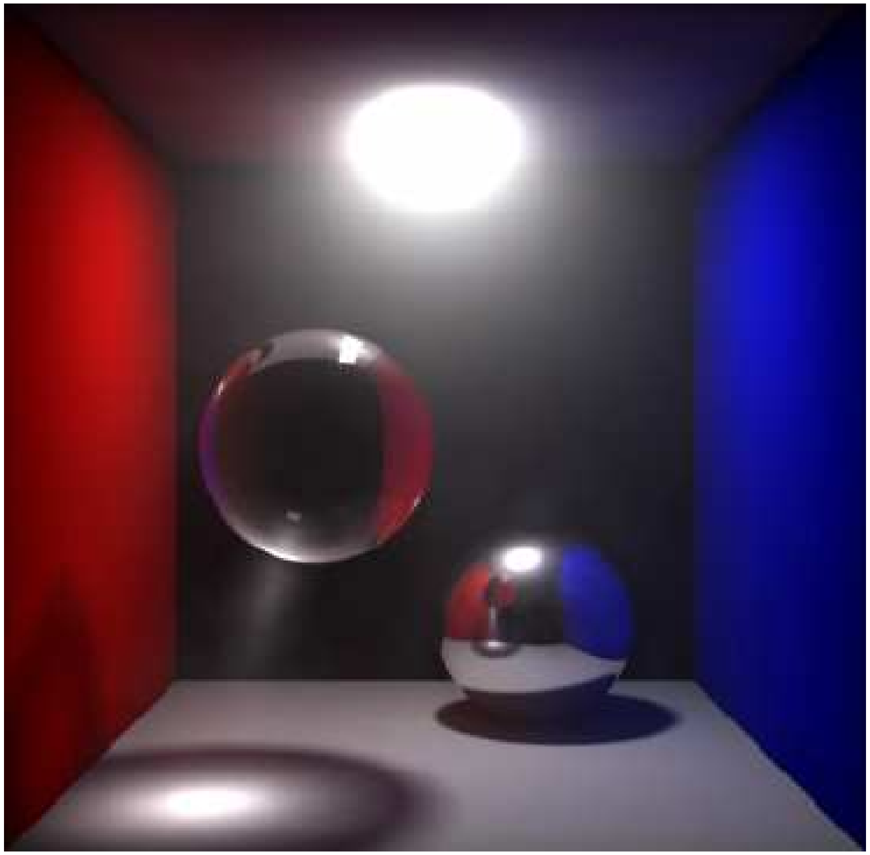

Clouds – anisotropic, nonhomogeneous participating mediums. Left – single scattering (rendered in 61 seconds); right – multiple scattering (map generated in 8 seconds, rendered in 92 seconds)

Images From the Paper



Cornell Box scene – isotropic, homogeneous participating medium. 200,000 photons used with 65,000 in the volume map. Radiance estimate used 100 photons. Maps generated in 4 seconds and image rendered in 3 minutes 32 seconds.

Images From the Paper



Cornell Box scene – anisotropic scattering in a homogeneous medium. Radiance estimate used 100 photons. Maps generated in 4 seconds and image rendered in 4 minutes 3 seconds.

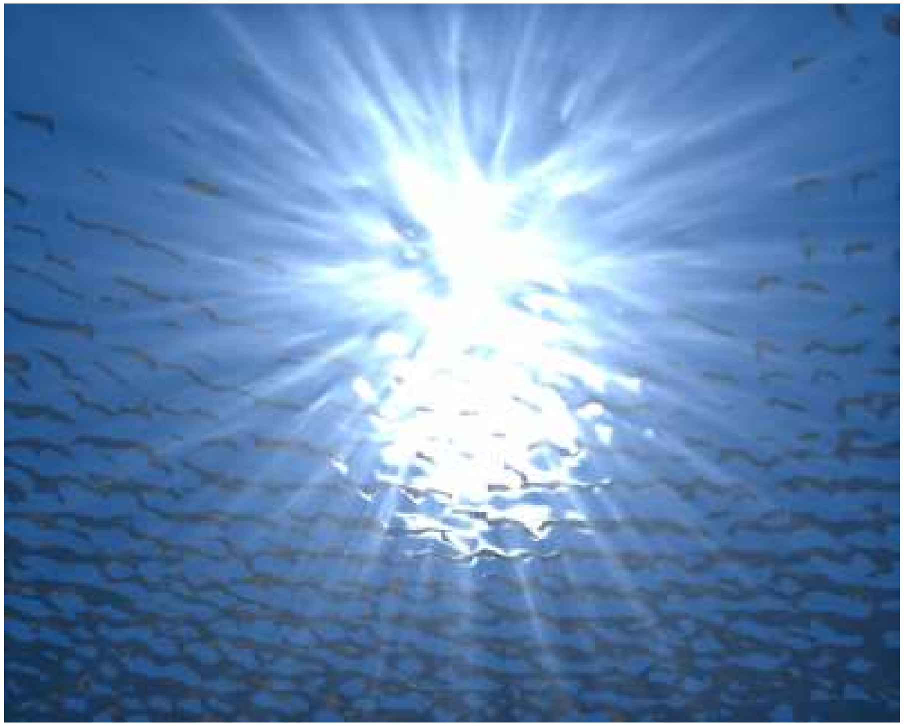
Images From the Paper

Cornell Box scene – anisotropic scattering in a nonhomogeneous medium. Generating maps with 200,000 photons took 6 seconds. Radiance estimate used 50 photons. Maps generated in 4 seconds and image rendered in 7 minutes 54 seconds.

Images From the Paper

Dusty room with stained glass window. 80,000 photons used to represent dusty air. 220,000 photons used to illuminate surfaces. Photon maps generated in 27 seconds and image rendered in 5 minutes 27 seconds.

Images From the Paper



Underwater sunbeams look nice!

Further Improvements

- Guiding photons to parts of scene which contribute most to image (visual importance)
  - Reduce number of photons required
  - Implement with importance map storing importance-carrying particles emitted from camera

References

- Jensen, Henrik Wann. “Efficient Simulation of Light Transport in Scenes with Participating Media using Photon Maps.” *Mental Images*,1998.
- Jensen, Henrik Wann. “Global Illumination using Photon Maps.” *Rendering Techniques*, 1996.
- Jensen, Henrik Wann. *Realistic Image Synthesis Using Photon Mapping*. 2001.


Questions?